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Evaluation of clean air delivery rates and operating cost effectiveness for room air cleaner and ventilation system in a small lecture room

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ABSTRACT

In general, room air cleaners are rated according to clean air delivery rate (CADR). However, ventilation systems have not yet been assessed using a metric similar to CADR. This study establishes a new mass balance equation that compares the CADRs of a ventilation system and a room air cleaner. Experiments and CFD simulations were conducted to evaluate and compare the CADRs of room air cleaners and ventilation system in the view of removing particles from indoor air. In addition, the operating cost effectiveness of ventilation system and room air cleaner was investigated. The results showed that the room air cleaners showed their performance independently, even when two or more room air cleaners were operated simultaneously. In the ventilation system, an air filter with MERV11 or higher rating was recommended to reduce the indoor particle concentration when 100% outdoor air was supplied. It was possible to select an air filter with MERV11or lower rating when the recirculation airflow rate was increasing up to 70%. The CADR of the room air cleaner was higher than that of the ventilation system regardless of the particle size and the filter performance when the airflow rate was same. The operating cost effectiveness (CADR/kW) of the room air cleaner was higher than that of the ventilation system at the same airflow rate. Therefore, the room air cleaner must be more cost-effective than the ventilation system for reducing particle concentration indoors.

1. Introduction

Ventilation and air cleaning techniques have been used for indoor spaces to improve indoor air quality [1]. Ventilation has been conventionally used to control the concentration of the particles and toxic gases, particularly, toxic substances. Indoor air cleaning has received an increasing amount of attention as a cost-effective method to reduce the concentration of indoor particles [1,2]. However, each of these techniques has weaknesses. Ventilation is challenging due to the energy consumption in buildings and the introduction of dirty outdoor air that is present in many cities, and air filters with modern technology cannot be used to remove toxic gases for long periods of time.

Many studies have been carried out to reduce the indoor particle concentration by using ventilation and indoor air cleaner. Recently, a study to determine the proper ventilation rate and filter grading was carried out by analyzing the mass balance and fan power equations to reduce both the particle concentration and the fan energy consumption in the home [3]. The energy-saving potentials of a ventilation system with an air cleaning unit and demand control were investigated in a multi residential building [4]. The impact of the air distribution method in ventilated rooms on the aerosol particle dispersion and removal was investigated through experiments and CFD simulation [5]. Fischer et al. investigated which time-varying ventilation strategy was good to reduce indoor particle concentration [6]. Persily provided a summary of ventilation metrics, measurement methods, and numerous field studies of ventilation rates in order to understand building performance in terms of energy consumption and indoor air quality [7].

Moreover, the primary effect (i.e., concentration reduction) and secondary effect (energy use and byproduct emissions) of indoor air cleaners were described by Siegel [1]. Noh and Oh showed that the CADR of room air cleaner can be expressed as the product of the effective air cleaning ratio (EACR), filtration efficiency, and flow rate [2]. Many indoor air cleaners were rated and compared according to clean air delivery rate (CADR) [8]. Sultan et al. tested various air cleaners that used different technologies and found that air cleaners with a HEPA filter and an electrostatic precipitator exhibit the best performance [9]. Shaughnessy and Sextro discussed the proper CADR to describe the room area and air cleaning effectiveness for different room sizes and air cleaner CADR ratings [10]. Novoselac and Siegel assessed the effect that the CADR of a portable

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air cleaner and its location had on the overall particle concentration in a residential zone [11]. Zuraimi et al. evaluated the effectiveness of portable air cleaners in removing airborne NaCl particles as an analogue for the influenza virus and applied an IAQ mass balance model to evaluate the performance of the system in controlling residential exposure and mitigating the risk of infection [12].

Even though many studies have been carried out to date, rarely has air cleaning performance of ventilation systems been compared to that of indoor air cleaners. Moreover, the operating cost effectiveness of ventilation system and room air cleaner was not compared until now.

This study evaluates and compares the performance of indoor air cleaner and ventilation system in removing indoor particles in a small lecture room. A mass balance equation with two different CADRs of indoor air cleaner and ventilation system was newly derived from the conventional mass balance equation. Experiments and CFD simulations were carried out to validate the new mass balance equation when the room air cleaners operated only. Mutual interference of room air cleaners was investigated when two or more room air cleaners are simultaneously operating. The certified CADRs of room air cleaners were re-assessed in a real scale lecture room regarding indoor particle removal. The CADRs of the ventilation system were then compared to those of room air cleaners with respect to the filter performance, ratio of the indoor to outdoor particle concentration, and the particle size. Finally, the operating cost effectiveness of ventilation system and room air cleaner was investigated and discussed.

2. Clean air delivery rates and operating cost effectiveness

2.1. Clean air delivery rates

Fig. 1 shows the modeled processes that have an effect on indoor particle concentration. The ventilation system, room air cleaning device, infiltration, particle deposition, particle generation, ventilation effectiveness and effective air cleaning ratio (EACR) are depicted. Here, the EACR refers to the predicted air mixing performance of an air cleaning device in a room, and it is rated on a scale from 0 to 1 [2].

The mass balance equation for particles can be expressed as in Eq. (1). For convenience, the expression for particle size, d_p (μm), is omitted in Eq. (1) through Eq. (5).

$$V\frac{dC_{in}}{dt} = \varepsilon_r\left[P_{vent}\cdot\left(\dot{Q}_{out}\cdot C_{out}+\dot{Q}_{re}\cdot C_{in}\right)-\left(\dot{Q}_{out}+\dot{Q}_{re}\right)\cdot C_{in}\right]$$
$$+\varepsilon_{ac}\left[P_{ac}\cdot\dot{Q}_{ac}\cdot C_{in}-\dot{Q}_{ac}\cdot C_{in}\right] \quad (1)$$
$$+P_{\inf}\cdot\dot{Q}_{\inf}\cdot C_{out}-\dot{Q}_{exf}\cdot C_{in}-V\cdot\dot{S}_{dep}\cdot C_{in}+\dot{G}$$

where C_{in} is the indoor particle concentration (#/m^3), C_{out} is the outdoor particle concentration (#/m^3), $\dot{Q}_{out}$ is the outdoor airflow rate (m^3/min), $\dot{Q}_{re}$ is the recirculation airflow rate (m^3/min) as shown in Fig. 1, $\dot{Q}_{ac}$ is the airflow rate of the room air cleaner (m^3/min), $\dot{Q}_{\inf}$ is the infiltration airflow rate (m^3/min), $\dot{Q}_{exf}$ is the ex-filtration airflow rate (m^3/min), P_{vent} is the penetration efficiency of a ventilation filter (−), P_{ac} is the penetration efficiency of the room air cleaner (−), $P_{\inf}$ is the penetration efficiency of particles due to outdoor air infiltration (−), V is the volume of a room (m^3), $\dot{S}_{dep}$ is the deposition rate of the particles in room, $\dot{G}$ is the generation rate of the particles in a space (#/min), t is the time (min), ε_r is the ventilation effectiveness (−), and ε_{ac} is the EACR of the room air cleaner (−). In general, there is a difference between the infiltration airflow rate and the ex-filtration airflow rate, but in this study, both airflow rates are assumed to be the same. The same applies to the in/out airflow rates for ventilation system.

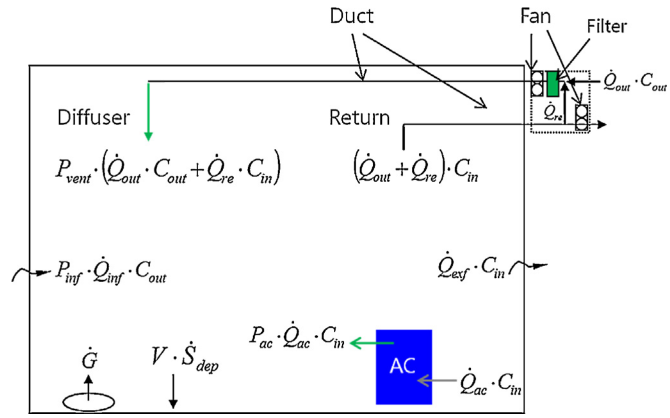

Fig. 1. Schematic of a mass balance model in a room with ventilation system and indoor air cleaner.

As shown in Eq. (1), the ventilation effectiveness and the EACR were used in order to consider the air mixing characteristics of ventilation system and room air cleaner, and to make correct predictions of the particle decay rates in indoor air. The air mixing characteristics of room air cleaners were defined as the EACR in Ref. [2] or the short-circuit factor in Refs. [13,15,16].

The first and second terms in the right hand side of Eq. (1) can be manipulated in respect to the indoor particle concentration, C_{in}, and therefore Eq. (1) changes as follows.

$$V\frac{dC_{in}}{dt} = -\varepsilon_r\cdot\left[\left(1-P_{vent}\frac{C_{out}}{C_{in}}\right)\cdot\dot{Q}_{out}+(1-P_{vent})\cdot\dot{Q}_{re}\right]\cdot C_{in}-\varepsilon_{ac}\cdot(1-P_{ac})\cdot\dot{Q}_{ac}$$
$$\cdot C_{in}+P_{\inf}\cdot\dot{Q}_{\inf}\cdot C_{out}+\dot{Q}_{exf}\cdot C_{in}-V\cdot\dot{S}_{dep}\cdot C_{in}+\dot{G}$$
$$=-\left[\varepsilon_r\cdot\left(1-P_{vent}\frac{C_{out}}{C_{in}}\right)\cdot\dot{Q}_{out}+\varepsilon_r\cdot(1-P_{vent})\cdot\dot{Q}_{re}+\varepsilon_{ac}\cdot(1-P_{ac})\cdot\dot{Q}_{ac}\right]\cdot C_{in}$$
$$+P_{\inf}\cdot\dot{Q}_{\inf}\cdot C_{out}-\dot{Q}_{exf}\cdot C_{in}-V\cdot\dot{S}_{dep}\cdot C_{in}+\dot{G} \quad (2)$$

$$CADR_{vent}=\varepsilon_r\cdot\left[\left(1-P_{vent}\frac{C_{out}}{C_{in}}\right)\cdot\dot{Q}_{out}+(1-P_{vent})\cdot\dot{Q}_{re}\right] \quad (3)$$

$$CADR_{ac}=\varepsilon_{ac}\cdot(1-P_{ac})\cdot\dot{Q}_{ac} \quad (4)$$

$$V\frac{dC_{in}}{dt}=-\left[CADR_{vent}+CADR_{ac}+\dot{Q}_{exf}+V\cdot\dot{S}_{dep}\right]\cdot C_{in}$$
$$+P_{\inf}\cdot\dot{Q}_{\inf}\cdot C_{out}+\dot{G} \quad (5)$$

In Eqs. (3) and (4), $CADR_{vent}$ and $CADR_{ac}$ indicate the clean air delivery rates of the ventilation system and the room air cleaner (m^3/min), respectively. In Eq. (2), the terms for the infiltration and ex-filtration have been left untouched since a specific airflow pattern cannot form as a result of infiltration and ex-filtration, such as for a ventilation system and a room air cleaner.

As shown in Eq. (3), the CADR of ventilation system can be defined as a function of the ventilation effectiveness, the penetration efficiency of the ventilation filter, the ratio of outdoor to indoor particle concentrations, the outdoor airflow rate, and the recirculation airflow rate, whereas the CADR of room air cleaner, shown in Eq. (4), can be expressed as the product of the EACR, the penetration efficiency of room air cleaner, and the airflow rate of room air cleaner. When the CADR is higher than zero, it means that the ventilation system or the room air cleaner can reduce the particle concentration in indoor air. Oppositely, when the CADR is lower than zero, it means that the indoor particle concentration will increase. From Eqs. (3) and (4), the CADRs for ventilation system and room air cleaner can be compared to each other.